

PLASMA IMMERSION ION IMPLANTATION APPARATUS AND METHOD

BACKGROUND OF THE INVENTION

Technical Field

[1] The present invention relates generally to plasma immersion, and more particularly to plasma immersion ion implanting via an apparatus having a conductive top section on a dielectric tophat plasma chamber configuration, an RF antenna having an active and parasitic antenna, and controlled gas flow.

Related Art

[2] Plasma apparatuses in semiconductor processing are widely used and accepted for etching and chemical vapor deposition (CVD). In addition, plasma apparatus are gaining in popularity for ion implantation. Relative to ion implantation, however, low throughputs at low energies with traditional ion implanting tools has made plasma immersion ion implant technology very attractive. Traditional plasma doping (PLAD) relies upon a negative voltage applied to a substrate to generate the plasma with the appropriate gas species, extract the positive ions and implant them into the substrate. At high implant voltage (i.e., above 3kV) this is an efficient means of generating ions. However, the bulk of PLAD's market is for low implant voltage, which is a very inefficient way of producing ions, thus reducing wafer throughput.

[3] One approach to conducting plasma immersion ion implantation is application of radio-frequency power (RF) to provide a source of ions, which can supply sufficient amounts of ions for implant independent of the voltage applied to the substrate. Whether the goal is to etch

circuit features, deposit layers of insulators or metals, or in this instance, implant ions into the wafer surface, one challenge is creating uniform plasma. This issue is especially important relative to ion implantation because a uniform ion flux impinging on the wafer is necessary. In particular, RF power must be applied in such a way that it will allow for a radially and azimuthally uniform plasma. The application of plasma immersion to ion implantation presents a number of unique challenges not faced relative to etching or CVD.

[4] Another challenge relative to ion implantation is addressing secondary electron emission from the wafer. In etching and CVD applications, secondary electron yield is minimal and hence the effect on apparatus design is irrelevant. However, in the area of ion implantation, the management of both heat load and charge carried by secondary electrons is extremely important. This problem is magnified for higher implant voltages where, for example, the number of electrons created from each incoming ion ranges from 5 to 10. The electrons are accelerated away from the substrate at the implant voltage, and the power carried by these electrons (up to 15 kW) is deposited in the chamber top. For RF energy to ionize a gas, it must pass through a dielectric, i.e., the portion of the chamber through which the RF energy is coupled must be an insulator. If, however, the chamber top is an insulator as is conventional, the secondary electrons cause the plasma-facing surface of the chamber top to charge to some voltage not at ground potential. As a consequence, the charged chamber top adversely affects implant uniformity energy and process repeatability.

[5] A number of approaches exist for conducting plasma processing. One approach, disclosed by Lam Corporation in US Patent No. 4,948,458, is to use a planer coil. Unfortunately, this approach results in excessive charging of the ceramic, which results in process variability. In

another approach promulgated by Novellus Corp. in US Patent No. 5,346,578, a hemispherical RF coupling window design is implemented. However, this approach suffers from similar issues with heat. In addition, charge removal becomes a major issue with this approach. In another approach that does not solve the above problem, Applied Material's US Patent No. 5,540,800 uses an RF coupling concept in which a combination of planar and hemispherical coils are used. Other plasma immersion ion implant approaches are disclosed by Silicon Genesis in US Patent No. 6,514,838 (multiple RF sources supported on single planar coupling window) and Axcelis in US Patent No. 6237,527. Each of these disclosures, however, suffer from similar issues associated with secondary electrons.

[6] Another challenge for plasma processing is plasma ignition. In particular, certain process gases may be difficult to ionize due to: their composition, pressure or the type of RF antenna or operating parameters (e.g., power and frequency). To address this problem a number of ignition assistance techniques have been employed. In one approach, an electric arc from a Tesla coil is used to assist ionization. In another approach, photoionization from high-intensity ultraviolet light may also assist in attaining ignition. However, none of these approaches adequately address difficult to ionize process gases that are practically impossible to ignite into a plasma (e.g., diborane in helium (15% B₂H₆ in 85% He) is extremely difficult to ionize). Difficulty in plasma ignition at a given set of desired process conditions limits the ability to operate at the optimum condition.

[7] Other challenges facing plasma ion implant immersion include, for example, contamination control, particulate control, ion density and uniformity, etch-deposition control and process control.

[8] In view of the foregoing, there is a need in the art for a way to provide uniform flux plasma immersion ion implantation that solves the problems of the related art.

SUMMARY OF THE INVENTION

[9] The invention includes a plasma immersion ion implant apparatus and method, and a plasma chamber, each configured to provide a uniform ion flux and to dissipate the effects of secondary electrons. The invention includes a plasma chamber including a dielectric tophat configuration and a conductive top section that may be liquid cooled. In addition, the invention provides a radio frequency (RF) antenna configuration including an active antenna that is coupled to an RF source and a parasitic antenna that is not coupled to any RF source and can be grounded at one point. The RF antenna allows for tuning of the RF coupling. A plasma igniter that provides a strike gas may also be provided to assist plasma ignition.

[10] A first aspect of the invention is directed to a plasma immersion ion implant apparatus comprising: a plasma chamber configured to receive a process gas; a radio frequency (RF) source configured to resonate radio frequency currents in a radio frequency antenna; a radio frequency antenna including an active antenna surrounding the plasma chamber and coupled to the RF source and a parasitic antenna surrounding the plasma chamber and not directly coupled to any RF source; and a platen for holding a target, wherein electro-magnetic fields induced by the radio frequency currents are effective to pass into the plasma chamber and excite and ionize the process gas to generate plasma within the plasma chamber.

[11] A second aspect of the invention is directed to a method of plasma immersion ion implantation, the method comprising the steps of: generating an ionic plasma by exposing a

process gas to a radio frequency (RF) source via a first active coil; tuning the ionic plasma by parasitically damping via a second parasitic coil that is not connected to any RF source; and implanting using the ionic plasma.

[12] A third aspect of the invention is directed to a plasma chamber comprising: a horizontal planar dielectric section for positioning above a platen; a vertical cylindrical dielectric section extending from the horizontal planar section; and a liquid cooled top conductive section coupled to the vertical dielectric section.

[13] The foregoing and other features of the invention will be apparent from the following more particular description of embodiments of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[14] The embodiments of this invention will be described in detail, with reference to the following figures, wherein like designations denote like elements, and wherein:

[15] FIG. 1 shows a plasma immersion ion implant apparatus according to the invention.

[16] FIGS. 2A-2C show graphs illustrating the effect of the number of parasitic coil turns (windings) on radial density profiles.

[17] FIGS. 3A-3B show graphs illustrating the effect of the number of parasitic coil turns (windings) on uniformity (FIG. 3A) and plasma density (FIG. 3B).

DETAILED DESCRIPTION OF THE INVENTION

[18] This invention covers plasma immersion ion implant apparatus based on a radio frequency (RF) inductively coupled configuration. Uniqueness of the RF source, plasma

ignition, material of selection of chamber parts, thermal and pressure management are covered, which both individually and comprehensively present optimal configuration details.

[19] Referring to the attached drawings, FIG. 1 shows a plasma immersion ion implant apparatus 10 according to the invention. Apparatus 10 includes a plasma chamber 20 configured to receive a process gas 22 from a gas source 24. A gas pressure controller 25 may be provided by, for example, a combination of upstream controller and a proportional valve 23. An exhaust port 27 is coupled to one or more vacuum pump(s) 29. Pressure controller 25 operates to maintain plasma chamber 20 pressure to a set value by fixing exhaust conductance and varying process gas 22 flow rate in a feedback loop including a pressure gauge 50 through which gas flows from the chamber 20 through port 52 and proportional valve 23 to allow for changing gas demand. In addition, a ratio control of trace gas species addition to plasma chamber 20 (not shown) may be provided by a mass flow meter in-line with the primary species flow. A separate gas injection (not shown) for in-situ conditioning species that includes silicon (Si) doped with the appropriate dopant to provide a uniform coating in the chamber and also prevent contaminants may also be provided. In addition, a multi-port gas injection scheme (not shown) to address neutral chemistry effects that result in across wafer variations may be provided.

[20] A radio frequency (RF) source 26 is configured to resonate radio frequency currents in a radio frequency antenna 28. RF source 26 is coupled, via an impedance match 42, to an active antenna 40 that surrounds plasma chamber 20. In one embodiment, a low RF frequency operation is preferred to minimize capacitive coupling, which minimizes sputtering of plasma chamber 20 walls that result in contamination and implantation between DC pulses: < 27 MHz such as 400 kHz, 2 MHz, 4 MHz or 13.56 MHz. RF source 26 can be either pulsed or

continuous. A parasitic antenna 44 also surrounds plasma chamber 20, but is not directly coupled to any RF source. In contrast, one point of parasitic antenna 44 is coupled to ground. Apparatus 10 also includes a platen 46 for holding a target 48, e.g., a semiconductor wafer, to be implanted.

[21] As shown in FIG. 1, plasma chamber 20 includes a horizontal planar section 60 positioned above platen 46, a vertical cylindrical section 62 extending from horizontal planar section 60, and a top section 64 coupled to vertical cylindrical section 62. In one embodiment, horizontal planar section 60 and vertical cylindrical section 62 include a dielectric material, and top section 64 is conductive. In terms of dielectric material, in one embodiment, a high purity ceramic is preferred to provide better protection against chemical and thermal attack. Typical material would be, for example, > 99.6% Al₂O₃ or AlN, although Yittria and YAG could also be used. In terms of conductive material, Al is one preferred embodiment. Top section 64 is preferably coupled to vertical section 62 with halogen resistant O-rings made of fluoro-carbon polymers, e.g., Chemrz and/or Kalrez materials. Top section 64 is also preferably mounted to vertical section 62 to minimize compression on the ceramic vertical section 62, but provide enough compression to seal with the O-ring between the ceramic and top section. Top section 64 is also DC/RF grounded.

[22] Top section 64 may also be liquid cooled via a passage 66 that receives a liquid coolant from a cooling source 70. The high energy levels required during PLAD processing introduce a considerable amount of unevenly distributed heat to the inner surfaces of plasma chamber 20. This heat is then unevenly translated through and along the surfaces of the chamber. This non-uniform heat creates temperature gradients that are high enough to cause thermal stress points

within the chamber geometry that are beyond the structural integrity of the fabrication material. As a result, plasma chamber 20 may be at risk of fracturing during current and future operation conditions. A conductive and liquid cooled top section 64 provides a ground reference for the plasma and allows removal of energy deposited by secondary electrons coming from platen 46. In other words, top section 64 removes the electric charge carried and the heat generated by the secondary electrons.

[23] Dielectric horizontal and vertical sections 60, 62 provide a mechanism for transferring RF power from RF antenna 28 to the plasma. The "tophat" configuration produced also allows for uniform RF power coupling, and thus uniform ion flux at target 48. In addition, the tophat configuration provides a mechanism for generating a radial and azimuthal ion implant uniformity, as described further below. The tophat configuration also provides a mechanism for obtaining an optimal ratio of chamber height to chamber diameter. The optimal ratio allows for, for example: the provision of a more uniform RF power coupling; reduction in the distance from target 46 to top section 64, which mitigates the effect of secondary electrons on the plasma density and chemistry; and provides a more uniform and repeatable implant through tailoring gas residence times by adjusting the chamber volume. In one embodiment, optimal ratios have been achieved by implementing chamber dimensions (in inches) as follows: $4.5 < L1 < 12$; $6.5 < L2 < 14$; $1.5 < H1 < 12$; and $1 < H2 < 5$. It should be understood, however, that optimal ratios may vary depending on plasma chamber 20 materials, process gas 22, RF energy provided and a variety of other parameters. Accordingly, the above example should not be considered limiting. In any event, a height of vertical section 62 is preferably minimized to remove secondary electrons before they collide with gas molecules.

[24] In one embodiment, as illustrated, active antenna 40 includes a horizontally-extending coil 80 and parasitic antenna 44 includes a vertically-extending coil 82. Each coil 80, 82 includes a plurality of turns (windings). As also shown, in one preferred embodiment, parasitic antenna 44 is above and coaxial with active antenna 40. In addition, an inner diameter of each antenna 40, 44 is greater than a size (e.g., diameter) of target 48. Parasitic coil 82 is not directly coupled to any RF source and, in one embodiment, has one end grounded, which provides a parasitic effect on the RF coupling that allows tuning. In one embodiment, an adjuster 90 for adjusting a number of turns of parasitic coil 82 providing a parasitic effect is provided. Adjuster 90 may include, for example, a metal short 92 between a floating end 94 of parasitic coil 82 and a desired coil turn. In an alternative embodiment, parasitic coil 82 is not directly coupled to any RF source and has both ends floating (not grounded), which may be selectively provided by a switch 97. It should also be recognized that which coil is parasitic can be changed by switching coil electrical couplings. That is, the horizontally-extending coil 80 could be parasitic while the vertically-extending coil 82 is coupled to RF source 26.

[25] One or more coils 80, 82 can also be formed such that it/they can be liquid cooled, e.g., each coil can be a tubular member, via a cooling source 70, which provides further reduction in temperature gradient generation. Although cooling source 70 has been shown as coupled to top section 64 and each coil 80, 82, it should be recognized that each part may have its own cooling source for customization purposes.

[26] In operation, an ionic plasma is generated by exposing process gas 22 to RF source 26 via a first active coil 40. In particular, plasma chamber 20 is first evacuated and then process gas 22 is introduced to the desired pressure. Typically, process gas 22 is continually being

simultaneously introduced and exhausted, and the gas flow rate and exhaust rate are tuned to achieve a constant pressure in plasma chamber 20. RF antenna 28 is then started such that electro-magnetic fields induced by the RF currents in RF antenna 28 are effective to pass into plasma chamber 20 and excite and ionize process gas 22 to generate plasma within the plasma chamber. Plasma ignition includes RF antenna 28 starting a very small number of free electrons moving in such a way that they ionize some process gas 22 molecules, releasing more free electrons that then ionize more gas molecules. The process continues until a steady state of ionized gas and free electrons exist within plasma chamber 20. The ionic plasma is tuned by parasitically damping via parasitic coil 44 that is not connected to any RF source. Implanting of target 48 is conducted using the ionic plasma by providing a negative voltage to target 48. Processing preferably is conducted under isobaric and isothermal conditions to minimize shock to the system, which reduces particulate contamination.

[27] With further regard to plasma ignition, in one embodiment, plasma immersion ion implant apparatus 10 may further include a plasma igniter 30. Plasma igniter 30 includes a reservoir 32 of easily-ionized gas 122 such as argon (Ar), which is referred to as a "strike gas," that assists in igniting a plasma. Reservoir 32 is coupled to a secondary gas inlet 34 to plasma chamber 20. Preferably, strike gas 122 is held in a small reservoir 32 of known volume and pressure with a high conductance connection to plasma chamber 20. Strike gas 122 is controllably introduced into plasma chamber 20 at a predetermined time by opening and then closing a shutoff valve 36, which is referred to as a "burst valve." This operation provides a short high-flow-rate burst to plasma chamber 20 for igniting a plasma. Strike gas 122 is exhausted from plasma chamber 20 normally by vacuum pump 29 such that the chamber quickly

returns to the desired processing conditions as the strike gas is exhausted. Plasma igniter 30 is easily integrated with pressure regulation during operation by pressure controller 25. In particular, when a strike gas 122 burst is introduced into plasma chamber 20, pressure controller 25 senses an increase in chamber pressure and correspondingly decreases process gas 22 flow.

[28] A strike gas profile (i.e., amplitude, shape and duration) of the burst of strike gas 122 is controlled by a number of factors such as length burst valve 36 is open, the pressure and volume of strike gas 122 in reservoir 32, the conductance of reservoir's 32 connection to plasma chamber 20 and the pumping speed of vacuum pump(s) 29 responsive to exhaust valve 18. One illustrative process gas that is difficult to ionize is diborane in helium (15% B₂H₆ in 85% He). However, using a strike gas 122 of argon (Ar) introduced for a time of 0.5-5 seconds from a limited conductance supply line at about 500 Torr produces a pressure burst of 20+ mTorr of Ar, allows easy and reliable ignition of this process gas.

[29] To provide for greater flexibility in defining a strike gas profile, a portion of reservoir 32 (e.g., the part farthest way from chamber 20) may optionally be intentionally separated by a conventional limited conductance 38, e.g., an orifice or metering valve, to provide a steady flow rate of strike gas 122 after the initial high-flow-rate burst. Reservoir 32 is refilled from a gas supply (not shown) after use once the reservoir is isolated from chamber 20 by burst valve 36. In an alternative embodiment, a strike gas source is plumbed directly to burst valve 36 using low conductance tubing such that no well-defined reservoir volume is defined. In this alternative embodiment, however, some control over strike gas pressure burst profile is lost.

[30] FIGS. 2A-2C illustrate the effect of the number of parasitic coil turns (windings) on radial density profiles. FIGS. 3A-3B illustrate the effect of the number of parasitic coil turns

(windings) on uniformity (FIG. 3A) and plasma density (FIG. 3B). As shown in FIG. 3A, more turns in the parasitic coil improves uniformity, while decreasing density, as shown in FIG. 3B.

[31] While this invention has been described in conjunction with the specific embodiments outlined above, it is evident that many alternatives, modifications and variations will be apparent to those skilled in the art. Accordingly, the embodiments of the invention as set forth above are intended to be illustrative, not limiting. Various changes may be made without departing from the spirit and scope of the invention as defined in the following claims.